CLOCKWORKING FLAVOR

ALONSO, AC. DILLON, KAMENIK, MARTIN-CAMALICH, ZUPAN JHEP 1810 2018 099 ARXIV:1807.09792

ADRIAN CARMONA BERMUDEZ

PRISMA+ CLUSTER OF EXCELLENCE MAINZ INSTITUTE FOR THEORETICAL PHYSICS

MIAPP WORKSHOP: FLAVOR 2019: NEW PHYSICS IN FLAVOR FROM LHC TO BELLE II

May 21, 2019
Slide 1/20
A CLOCKWORK SOLUTION TO THE FLAVOR PUZZLE
The Clockwork Mechanism

Generic mechanism to generate large hierarchies:

• in couplings

\[ g_{\text{eff}} = g \times q^{-N} \]

\[ \frac{1}{q} \times \frac{1}{q} \times \ldots \times \frac{1}{q} \text{ N - times} \]

• in scales

\[ \Lambda_{\text{eff}} = M/g_{\text{eff}} \]

It is used to solve the hierarchy problem such that

\[ \nu_{\text{EW}} \sim M_{\text{Planck}} \times q^{-N} \]

In some cases, it can be viewed as the deconstructed version of the Linear Dilaton Model

[Antoniadis, Arvanitaki, Dimopoulos, Giveon, '11][Baryakhtar, '12][Cox, Gherghetta, '12]
**Clockworking a single fermion**

One chiral fermion $\psi_{R,0}$ plus $N$ vector-like fermions $\psi_k$

\[ \psi_R = i \sum_{j=0}^{N} \bar{\psi}_{R,j} D \psi_{R,j} + i \sum_{j=1}^{N} \bar{\psi}_{L,j} D \psi_{L,j} - m \sum_{j=1}^{N} (\bar{\psi}_{L,j} \psi_{R,j} - q \bar{\psi}_{L,j} \psi_{R,j-1}) + \text{h.c.}, \]

- We have $2N + 1$ chiral symmetries broken by $2N$ mass parameters $(q, mq) \Rightarrow$ We end up with a massless chiral state

- We assume all sites to share the same gauge group, i.e., $D$ is not site dependent
This pattern leads to a $N \times (N + 1)$ mass matrix,

$$M_\psi = m \begin{pmatrix} -q & 1 & 0 & \ldots & 0 \\ 0 & -q & 1 & \ldots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \ldots & 0 & -q & 1 \end{pmatrix},$$

which leads, after diagonalization, to a mass spectrum

$$M_k^2 = m^2 \left( 1 + q^2 - 2q \cos \left( \frac{k\pi}{N+1} \right) \right)$$

- Mass gap $M_1 \approx m(q - 1)$
- Mass splitting $M_N - M_1 \approx 2m$

[Giudice, McCullough, '15]
We are interested in the 0-site components $f^k_\psi$, i.e.,

$$
\psi'_R, k = \sum_{j=0}^{N} V^R_{jk} \psi_R, j, \quad f^k_\psi = V^R_{0k}, \quad k = 0, \ldots, N,
$$

$$
f^0_\psi = \begin{cases} 
\sim 1/q^N, & q \gg 1; \\
\frac{1}{\sqrt{1+N}}, & q \to 1.
\end{cases}
$$
• One clockwork chain per SM chiral fermion \((q_{\psi_i}, N_{\psi_i})\), with the corresponding massless state identified with its SM counterpart

• The Higgs doublet lives in the 0-site

\[
\bar{Q}_{L,0} Y_D H d_{R,0} + \bar{Q}_{L,0} Y_U \tilde{H} u_{R,0} + h.c
\]
A CLOCKWORK MODEL OF FLAVOR

The SM-like Yukawas are given by

\[
(Y_{SM}^u)_{ij} = f_{Q(i)} (Y_{U})_{ij} f_{u(j)} \sim q_{Q(i)}^{-N_{Q(i)}} (Y_{U})_{ij} q_{u(j)}^{-N_{u(j)}}
\]

\[
(Y_{SM}^d)_{ij} = f_{Q(i)} (Y_{D})_{ij} f_{d(j)} \sim q_{Q(i)}^{-N_{Q(i)}} (Y_{D})_{ij} q_{d(j)}^{-N_{d(j)}}
\]

We can have hierarchical quark masses for \( O(1) \) proto-Yukawas if

\[
\begin{align*}
q_{Q(1)}^{-N_{Q(1)}} & \ll q_{Q(2)}^{-N_{Q(2)}} \ll q_{Q(3)}^{-N_{Q(3)}} \\
q_{u(1)}^{-N_{u(1)}} & \ll q_{u(2)}^{-N_{u(2)}} \ll q_{u(3)}^{-N_{u(3)}} \\
q_{d(1)}^{-N_{d(1)}} & \ll q_{d(2)}^{-N_{d(2)}} \ll q_{d(3)}^{-N_{d(3)}}
\end{align*}
\]

which leads to

\[
\begin{align*}
\bar{m}_{u(i)} & \sim v f_{Q(i)} f_{u(i)} \\
\bar{m}_{d(i)} & \sim v f_{Q(i)} f_{d(i)} \\
|L_{u,d}|_{ij} & \sim f_{Q(i)}/f_{Q(j)} \\
|R_{u,d}|_{ij} & \sim f_{u,d(i)}/f_{u,d(j)} \\
(V_{CKM})_{ij} & \sim f_{Q(i)}/f_{Q(j)}
\end{align*}
\]
There are two special limits

1. The universal $q$ limit (or the FN limit)

   $$ q \sim \frac{1}{\lambda} \gg 1 \quad \text{fixed and} \quad N_{Q(1)} \gg N_{Q(2)} \gg N_{Q(3)}, \ldots $$

   - The total number of VLQs can be somehow reduced
   - $q \sim \frac{1}{\lambda} \gg 1 \Rightarrow M_k \sim q m$ \hspace{1cm} Compressed spectra

2. The universal $N$ limit (or the RS limit)

   $$ N \gg 1 \quad \text{fixed and} \quad q_{Q(1)} \gg q_{Q(2)} \gg q_{Q(3)}, \ldots $$

   - A very large number of VLQs, $12 \times N$
   - For the third generation $q \sim 1 \Rightarrow M_1 \approx m(q - 1) \ll m$ Light gears

But we can find all kind of intermediate situations!
CW as the EFT of some new FN

- The CW models of flavor do not contain a dynamical flavon.

- The differences between the universal-\(q\) CW and the FN models will depend on the values of \(m_{\text{arg}\phi}\) and \(m_{\text{rad}\phi}\).

- The universal-\(q\) CW can be seen as the low energy effective theory – for some range of the parameter space – of a different realization of Froggatt-Nielsen where \(U(1)_H\) is non-anomalous and

\[
(Y_{u}^{\text{SM}})_{ij} \sim \left( \frac{\Lambda}{\langle \phi^* \rangle} \right)^{N_{Q(i)} + N_{u(j)}}
\]

- If \(U(1)_H\) is gauge, the new gauge boson have mass \(m_H \sim g_H \langle \phi \rangle\) and mediate FNCNs \(\Rightarrow m_H\) can be light enough if \(g_H\) is small [Zupan et al, soon]
PHENOMENOLOGY
Modification of $\alpha_s$ and $\lambda$ RGEs

$Z/W$ couplings modification

$h/Z$ FCNCs

Neutral meson mixing

Collider Physics

Collider searches on VLQs
LOW ENERGY CONSTRAINTS

All these light gears will mess up with flavor data and EWPO; at $\mathcal{O}(\frac{v^2}{M^2})$

However, there is some Clockwork-GIM mechanism helping with FCNCs. For instance, $Z_d L(i) d_L (j)$ receives corrections

$$[\delta g_L]_{ij}^{Z_d} = \frac{v^2}{4} f_{Q(i)} f_{Q(j)} \left[ Y_D M_d^{-2} Y_D^\dagger \right]_{ij}$$

A strong constraint comes from $\bar{Z}b_L b_L$ since is not protected as $f_{Q(3)} = 1$

$$\Rightarrow M_{d(i)} \gtrsim 3.8 \text{ TeV}$$
Low Energy Constraints

For neutral-meson mixing $K - \bar{K}, B - \bar{B}, D - \bar{D}, \ldots$ we have

- Tree-level $\mathcal{O}(v^4/M^4)$ contributions

  \[ \psi_j \psi_j \psi_i \psi_i \]

  \[ Z \]

- One loop $\mathcal{O}(v^2/M^2)$ terms (finite pieces and mixing terms)

  \[ \psi_j \psi_i \]

  \[ \psi_j \psi_i \]

  \[ \psi_j \psi_i \]

  \[ \psi_j \psi_i \]

However, they still come with a large overlap supression!
Assuming $q \sim 1/\lambda$ and $N_{\psi(i)}$ such

$$F_Q = \text{diag}(\lambda^3, \lambda^2, 1), \quad F_u = \text{diag}(\lambda^4, \lambda, 1), \quad F_d = \text{diag}(\lambda^4, \lambda^3, \lambda^2),$$

we obtain
LOW ENERGY CONSTRAINTS

Assuming \( q \sim 1/\lambda \) and \( N_{\psi(i)} \) such

\[
F_Q = \text{diag}(\lambda^3, \lambda^2, 1), \quad F_u = \text{diag}(\lambda^4, \lambda, 1), \quad F_d = \text{diag}(\lambda^4, \lambda^3, \lambda^2),
\]

we obtain

<table>
<thead>
<tr>
<th>Process</th>
<th>U</th>
<th>D</th>
<th>Q</th>
<th>UQ</th>
<th>DQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_s-\bar{B}_s )</td>
<td>( \lambda^4 ), ( \Box^\ast )</td>
<td>( \lambda^4 ), ( \times ) and ( \Box )</td>
<td>( \lambda^7 ), ( \Box^\ast )</td>
<td>( \lambda^7 ), ( \Box )</td>
<td>( \lambda^6 ), ( \times )</td>
</tr>
<tr>
<td>( B-\bar{B} )</td>
<td>( \lambda^6 ), ( \Box^\ast )</td>
<td>( \lambda^6 ), ( \times ) and ( \Box )</td>
<td>( \lambda^9 ), ( \Box^\ast )</td>
<td>( \lambda^9 ), ( \Box )</td>
<td>( \lambda^8 ), ( \times )</td>
</tr>
<tr>
<td>( K-\bar{K} )</td>
<td>( \lambda^{10} ), ( \Box^\ast )</td>
<td>( \lambda^{10} ), ( \times ) and ( \Box )</td>
<td>( \lambda^{12} ), ( \Box^\ast ) ( \dagger )</td>
<td>( \lambda^{12} ), ( \times ) ( \dagger )</td>
<td>( \lambda^{12} ), ( \times ) ( \dagger ) and ( \Box ) ( \dagger )</td>
</tr>
<tr>
<td>( D-\bar{D} )</td>
<td>( \lambda^{10} ), ( \times ) and ( \Box )</td>
<td>( \lambda^{10} ), ( \Box )</td>
<td>( \lambda^{10} ), ( \times ) and ( \Box )</td>
<td>( \lambda^8 ), ( \times ) ( \dagger )</td>
<td>( \lambda^{10} ), ( \Box ) ( \dagger )</td>
</tr>
</tbody>
</table>
Collider Phenomenology

Benchmark with $M_u \gtrsim 1.3$ TeV, $M_d \gtrsim 1.5$ TeV, $M_Q \gtrsim 1.7$ TeV
Collider Pheno
Top Partner Searches

\[ pp \rightarrow \bar{Q}Q \rightarrow \bar{Q} + tW/H/Z \]
• The CW mechanism can also provide a rationale for the flavor puzzle

• There are two interesting limits, corresponding to universal values of $q$ or $N$, which point to rather different UV completions

• The universal-$q$ limit can be most easily matched to a different limit of the usual FN models, which we called clockworked FN

• These models are embedded with some CW-GIM flavor protection that allows to have very light gears

• We have put forward new ways of looking for such a peculiar fermion spectrum at colliders
THANKS!
BACK-UP SLIDES
QCD Landau Pole

Having a bunch of heavy quarks will affect the running of $\alpha_s$. Restricting ourselves to one loop,

$$\frac{d\alpha_s}{d\ln \mu} = -2\beta_0 \frac{\alpha_s^2}{4\pi}, \quad \beta_0 = \frac{11N_c - 2N_f}{3},$$

\[\Lambda_{\text{Landau}} > 10M\]

\[\Lambda_{\text{Landau}} > 100M\]
$\beta_\lambda \supset 12 \text{Tr} \left( Y^\dagger_U Y_U \right) \lambda - 12 \text{Tr} \left( Y_U Y^\dagger_U Y_U Y^\dagger_U \right)$

$\beta_\lambda$ receives very large contributions from sizable Yukawas!

Therefore, we should have Yukawa entries a bit smaller than 1 to have

$$\text{Tr} \left( Y^\dagger_U Y_U Y^\dagger_U Y_U \right) + \text{Tr} \left( Y^\dagger_D Y_D Y^\dagger_D Y_D \right) \ll \frac{4\pi^2}{3}$$

This really disfavours the CW universal $N$ limit since $y_t \sim (Y_U)_{33}/(1 + N)$

However, one could add extra scalars or gauge bosons like e.g. [Sannino, Smirnov, Wang '19]
BENCHMARK WITH $M_u \gtrsim 1.3$ TeV, $M_Q \gtrsim 1.7$ TeV, $M_d \gg M_u, Q$
Collider Pheno
Top Partner Searches

$pp \rightarrow \bar{Q} Q \rightarrow \bar{Q} + tW/H/Z$

1806.01762

1803.09678